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DESCRIPTION AND PRELIMINARY FLIGHT INVESTIGATION OF AN INSTRUMENT FOR DETECTING SUBNORMAL ACCELERATION DURING TAKE-OFF

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SUMMARY

An evaluation has been made of a prototype instrument designed to give an immediate indication of loss in airplane acceleration due to power deficiency or increased resistance at any time during take-off at which the pilot still has a choice of continuing or stopping. The principal components of this instrument are a linear accelerometer and a pressure diaphragm coupled together so that the normal decrease in acceleration with increasing velocity during take-off is compensated by the increase in dynamic pressure in order to give a constant predictable indicator reading as long as the thrust and resistance are normal.

Satisfactory operation of the instrument requires that no substantial variation in attitude of the airplane occurs up to the speed beyond which the pilot can no longer safely stop the take-off. Measurements made of attitude angle and longitudinal accelerations during the take-off on three widely different types of tricycle-geared airplanes indicated that at least for these cases the variation of attitude angle was within tolerable limits. A simplified prototype of the proposed instrument was tested in a tricycle-geared jet trainer. The tests revealed a low-frequency oscillation in the indication which, although undesirable, would not unduly interfere with reading the instrument. The indication remained essentially constant throughout the take-off up to nose-wheel lift-off when full power was maintained. Response of the indication to simulated partial power loss was immediate and the indication was consistent for given power settings in different take-offs.

INTRODUCTION

Ability of the pilot to recognize quickly any appreciable deficiency in airplane acceleration during take-off is becoming increasingly important as performance during take-off becomes more critical. The use of high wing loadings and wings with lower maximum-lift capabilities, particularly on the newer jet airplanes, has resulted in smaller take-off performance margins on existing runways. Crashes have occurred in take-off because of the pilot's apparent inability to recognize the fact that the airplane performance was less than that predicted by the use of available meteorological data and take-off charts. Losses in airplane take-off performance can occur from a loss in thrust, an increase in rolling or aerodynamic resistance, or meteorological conditions different from those used in the take-off calculations.

An instrument designed to aid the pilot in detecting malfunction of the airplane during take-off has been proposed in the Langley Flight Research Division. Some preliminary flight tests were made to verify assumptions on which the design of the instrument is based. A simplified version of the instrument was then constructed and installed in an airplane for evaluation in take-off. A description of the instrument and the results of the flight tests are reported herein.

SYMBOLS

A effective diaphragm area

a_h airplane longitudinal acceleration referred to horizontal plane, g units

a_x longitudinal acceleration referred to airplane axes (accelerometer response), g units

b moment arm of diaphragm action

C_D drag coefficient

C_L lift coefficient

F thrust

F_{st} static thrust

dF/dq rate of change of thrust with dynamic pressure

f_{D_e} effective drag area of airplane including factors to take account of decrement in thrust and friction with increasing speed as well as aerodynamic drag, $C_DS - \mu C_LS + \frac{dF}{dq}$

g acceleration due to gravity

p_T total pressure, $q_c + p$

K spring constant of diaphragm

l moment arm of accelerometer mass

p static pressure

q dynamic pressure, $\frac{1}{2}\rho V^2$

q_c impact pressure (approximately equal to q for speeds attained during take-off)

S wing area

W airplane weight

w accelerometer-element weight

V airspeed

μ coefficient of friction between wheels and ground

δ deflection of diaphragm

θ attitude angle of accelerometer unit from horizontal

ρ mass density

BASIC DESIGN CONSIDERATIONS

The immediate recognition of a malfunction of an airplane in take-off, whether caused by loss of thrust or increased resistance, is dependent on the sensing of a change in acceleration. However, a simple longitudinal accelerometer alone would not be suitable as a detector since the acceleration of an airplane normally decreases in take-off as a result of increasing aerodynamic drag and decreasing net thrust. The pilot might, therefore, be unable to distinguish between a deficiency in acceleration due to malfunction and the normal decrease in acceleration after the take-off is under way.

However, by incorporating a dynamic-pressure sensing element with the longitudinal accelerometer, the decrease in acceleration with increasing speed could be compensated for to give a constant predictable reading as long as the airplane functions properly within the limits prescribed herein. A loss in acceleration at the start of and during the take-off would therefore be quickly detectable as a departure of the indication from the expected constant value. An obvious shortcoming in the use of an accelerometer element, if it is fixed with respect to the airplane, is that it would respond not only to horizontal acceleration, as desired, but also to variations in attitude angle of the airplane. It was thought, however, that with many modern airplanes the attitude angle while the airplane is on the ground is constrained within small limits by the arrangement of the tricycle- or bicycle-type gears so that variations in attitude angle during the part of the take-off of primary concern (up to the critical speed, that is, the speed beyond which the pilot can no longer stop the take-off) might not be a serious problem. The validity of this assumption is discussed later.

Equation of motion of the airplane.- The motion of an airplane accelerating in the take-off at a constant attitude angle may be expressed as

$$Wa_h = F_{st} - \frac{dF}{dq} q - C_D Sq - \mu(W - C_L Sq) \tag{1}$$

which may be rearranged

$$a_h = \frac{F_{st}}{W} - \mu - \frac{q}{W}\left(C_D S - \mu C_L S + \frac{dF}{dq}\right) \tag{2}$$

and for small angles

$$a_h = a_x - \theta$$

where θ is measured in radians. Now, if a constant angle of attack in the take-off, a constant friction coefficient, and a constant value of dF/dq are assumed, the term $C_D S - \mu C_L S + \frac{dF}{dq}$ can be replaced by a constant which for convenience may be designated effective drag area f_{D_e} of the airplane. Assume, in addition, that the accelerometer unit is initially alined with the horizontal ($\theta = 0$) and that the attitude remains constant, then

$$a_x + \frac{q}{W} f_{D_e} = \frac{F_{st}}{W} - \mu \tag{3}$$

and for a given take-off condition (fixed value of gross weight and static thrust)

$$a_x + \frac{q}{W} f_{D_e} = \text{Constant} \tag{4}$$

The terms in equation (3) are illustrated in figure 1, which shows the variations of a_x and $\frac{q}{W} f_{D_e}$ that have been calculated for the take-off of a multiengine jet bomber. Results are included to represent both a properly functioning take-off and a take-off in which an engine failure occurs at a dynamic pressure of 19 pounds per square foot (indicated airspeed of about 75 knots).

Equations of forces in the instrument.- The basic design of the instrument is illustrated schematically in figure 2. As shown in the illustration, a constant reading on the scale is maintained in a normal take-off by an equilibrium of moments due to forces resulting from longitudinal acceleration, from impact pressure acting on the diaphragm, and from the spring force of the diaphragm. A constant dial reading is maintained in a normal take-off within limits presented because the decrease in the moment of the accelerometer element is compensated for during the take-off by an increased moment from the airspeed diaphragm resulting from increased dynamic pressure. This principle of compensating force changes must be related to the addition of a_x and $\frac{q}{W} f_{D_e}$ as, for example, shown in figure 1. The equilibrium of moments in the instrument is given by the following equation:

(Moment from accelerometer element) = (Moment from airspeed diaphragm)

$$w a_x l = -b(Aq - K\delta) \tag{5}$$

or

$$a_x + \frac{bAq}{wl} = \frac{bK\delta}{wl} \tag{6}$$

In order that δ may be independent of forward speed, the terms in equation (6) for the instrument must be related to the terms in equation (3) for the airplane in the following manner:

$$\frac{bA}{wl} = \frac{f_{D_e}}{W} \tag{7}$$

or

$$l = \frac{WA}{wf_{D_e}} b \tag{8}$$

Then, the term for the instrument, on the left-hand side of the equation, must be related to the term for the airplane, on the right-hand side of the equation, as follows:

$$\frac{bK\delta}{wl} = \frac{F_{st}}{W} - \mu \tag{9}$$

Combining equations (8) and (9)

$$\delta = \frac{A}{Kf_{D_e}}\left(F_{st} - \mu W\right) \tag{10}$$

Equation (8) shows that the moment arm of the accelerometer element in the instrument must be adjustable to allow for variations in gross weight and effective drag area of the airplane, and equation (10) indicates that with this adjustment the deflection of the needle on the dial of the instrument will be independent of forward speed and proportional to the zero-speed excess thrust since the other terms are assumed constant. It can be seen that a given decrement in acceleration such as might result from a loss of thrust would be indicated quantitatively as a comparable percentage change in dial deflection.

Additional considerations in the design.- The adjustment of the arm length l (fig. 2) can be made a function of weight change alone if the assumption is made that for a given airplane the effective drag area will be fixed, that is, that the drag configuration, including flap position and external store installations, will not be changed. Otherwise, the relation between arm length and airplane weight would have to be changed in accordance with equation (8). The assumption of constant effective drag area f_{D_e} for a given airplane also implies that the value of dF/dq or rate of change of thrust with dynamic pressure included in this factor is independent of speed and atmospheric conditions. This implication is not true. However, the contribution of dF/dq to the value of f_{D_e} is generally small and the effect of variations in this factor on the indications of the instrument should be sufficiently small to justify this assumption.

The discussion of the take-off indicator so far has been based on the premise that the weight of the airplane at take-off will always be known within close limits (1 or 2 percent). If the weight estimate is in error, then the take-off distance predicted from the regular airplane take-off charts will also be in error. If the weight setting of the take-off indicator involves the same error, then the deflection of the needle on the dial will be less or greater than the predetermined value depending on whether the weight is underestimated or overestimated, respectively. The indication would therefore be in the right direction to show whether the actual take-off would be longer or shorter than predicted but it would not be quantitatively correct. That is, a given percentage difference in either initial excess thrust or weight (for a fixed weight setting of the instrument) would result in the same percentage change in indicator reading but in terms of take-off distance would cause approximately the same percentage change in one case (thrust) and approximately twice the percentage change in the other case (weight). Under certain circumstances the instrument might indicate a reading in the wrong direction with respect to the difference in take-off distance; for example, if the initial excess thrust were 7 percent in excess of the expected value and the weight were underestimated by 5 percent, the indicator reading would show a favorable margin from which it would be expected that the take-off would be about 3 percent shorter than predicted, whereas it would actually be 3 percent longer. For the successful use of this instrument, therefore, the weight of the airplane must be known accurately.

Illustrative example of the take-off instrument.- In order to show a possible general arrangement of the take-off indicator including external adjustment knobs, an illustrative schematic sketch is presented in figure 3. Many liberties have been taken, for convenience of illustration, with the sizes and arrangement of elements of the mechanism; for example, the axis of rotation of the accelerometer element, which is shown horizontal, would be vertical in an actual instrument to avoid the influence of vertical acceleration.

Adjustment of the lever arm of the accelerometer mass is accomplished by means of an external knob and a gear train. Pushing in the external weight knob simultaneously engages the gear systems for adjustment of the lever arm and movement of the indicator for the airplane weight scale.

With the adjustment for airplane weight properly set in, the position of the indicator needle during take-off will then be a function only of the initial excess thrust (for a fixed aerodynamic configuration), that is, the difference between the static thrust and the rolling friction of the wheels. Because the expected full-throttle static thrust of the engines is a known function of atmospheric pressure and temperature, this information can be incorporated in a simple chart, account being taken of the effect of weight on rolling friction (the coefficient of rolling friction μ can generally be taken as 0.02 for dry concrete runways) and the calibration constants of the instrument. From this chart the reading that the instrument should have during take-off, if the airplane is functioning properly, can be determined. An example of this chart is given in figure 4. The procedure for reading the chart is shown for a temperature of 40° F, a pressure altitude of 3,000 feet, and a weight of 150,000 pounds; these values give a dial-setting reading of 27.9. The chart reading can then be set into the instrument to provide a reference for the actual reading.

The predicted position of the indicator needle in take-off, as determined from the chart, can be set into the instrument by means of an external knob geared to a rotatable dial on which are marked an arrow and a suitable scale around the rim starting with zero at the arrow. The dial is rotated until the number on the dial corresponding to the chart reading is in line with the indicator needle. This setting is made with the airplane standing still and with the engines idling or stopped to avoid a nose-down moment due to braking and a possible change in attitude angle which is not present with the airplane running with brakes released in the take-off. Because the instrument is sensitive to changes in attitude angle, as discussed previously, setting the dial with respect to the static position of the indicator needle should automatically compensate for small variations in ground attitude angle caused by variations in airplane loading.

In a take-off the indicator needle will swing quickly from its static position to alinement with the arrow on the dial if the airplane is functioning according to expectations. If the thrust is below normal or there is excessive resistance, the needle position will fall short of the reference pointer; thus a longer take-off run than expected is indicated.

In order that an indication of subnormal performance might have some significance to the pilot in terms of the increase in take-off run that will be required, some provision to meet this need should be incorporated in the instrument. It was found from calculations that, for all conditions under which take-offs are likely to be made, a given percentage change in initial excess thrust (or take-off indicator reading) will result in nearly a fixed percentage change in take-off distance. It appears therefore that, if a secondary reference is provided on the instrument dial with provision to maintain it at an interval below the primary reference arrow which is a constant percentage of the reference arrow or dial setting, this interval could be considered as representing, closely enough, a constant percentage increase in take-off run for all conditions. (A typical value of the interval would be about 7 percent of the dial setting for a 10-percent increase in take-off run.) In the arrangement shown in figure 3, this secondary reference is obtained by means of a subdial geared to the dial-setting knob at a lower gear ratio than the main dial. A segment of contrasting color to that of the main dial is painted on the subdial and exposed by a window cut in the main dial adjacent to the primary reference arrow. The extent of exposed colored region is thereby automatically adjusted to maintain it at the proper percentage of the primary reference setting when the primary reference or dial setting is adjusted. For applications where the expected range of dial settings is not expected to be large, it may be sufficient to provide a fixed secondary reference on the main dial.

If elimination of the use of a chart is considered desirable, a refinement of the instrument is possible that will allow the pilot to make the necessary preflight adjustments by means of knobs having scales for airplane weight, atmospheric temperature, and barometric pressure. The instrument would require a computing mechanism that would account for the variations of static thrust with atmospheric pressure and temperature and the variation of rolling resistance with weight.

FLIGHT TESTS

Measurements to verify basic assumptions.- Before construction of an instrument, flight tests were made to determine the extent of attitude change during the take-off run as well as the linearity of the variation of acceleration with impact pressure. Measurements were made of impact pressure and longitudinal acceleration during take-offs of a multiengine propeller-driven bomber equipped with a tricycle landing gear. Extensive instrumentation of this airplane for another investigation allowed detailed measurements of strut and tire deflections and thus permitted an accurate determination of attitude angle. The results of the measurements are shown in figure 5. The attitude angle remained constant within 0.004 radian $\left(\frac{1}{4}^{\circ}\right)$ throughout the take-off until action was taken to lift the nose wheel just before lift-off. This variation in attitude angle would cause an error of only 0.004g or about 1 percent in the horizontal acceleration as measured in this airplane with a longitudinal accelerometer and, hence, is sufficiently small to permit the use of the proposed instrument. The variation of acceleration with impact pressure is shown in figure 5 for several take-offs. These results indicate that the relation between acceleration and impact pressure is essentially linear and consistent. Data points at the start of the take-off have been eliminated from the plot because the pilot was using brakes to maintain heading.

Measurements of longitudinal acceleration and impact pressure were also obtained during take-off of a tricycle-geared jet fighter equipped with an afterburner. The results are shown in figure 6. Here again the variation in acceleration with dynamic pressure is apparently linear. The fluctuation of about ±0.01g in the accelerometer reading about the linear variation probably reflects a rocking motion of the airplane $\left(\text{about} \pm \frac{1}{2}^{\circ}\right)$ which, although larger than the attitude variation of the bomber, is still within the limits required for satisfactory use of the proposed take-off indicator.

Tests of preliminary instrument.- With the evidence that at least for some airplanes the variation of attitude angle is small during a substantial part of the take-off, the design and construction of a preliminary instrument was undertaken for evaluation of the practicability of the device. This instrument incorporates the main principles outlined above. Inasmuch as the instrument was intended only for test purposes, it did not include provisions for external adjustment of the accelerometer sensitivity to compensate for airplane weight changes or means for setting a reference pointer at the expected reading. The indicator dial is simply marked in degrees of angular displacement of the indicator needle. A photograph of the instrument is shown as figure 7.

The instrument with the accelerometer-element sensitivity adjusted according to equation (8) for take-off weight and estimated effective drag area was installed in a jet trainer equipped with tricycle landing gear. A preliminary check of the setting of the instrument was obtained by having the pilot monitor it during a take-off. Provision was then made for obtaining detailed observations of its performance by photographing the instrument together with the engine-speed and airspeed indicators. A 16-millimeter gun camera set at 24 frames per second was used. Three take-offs were made within about $1\frac{1}{2}$ hours during which time atmospheric conditions remained essentially constant. The plane was refueled after each take-off in order to maintain the weight as nearly constant as possible.

The results of the three tests are shown in figure 8 as time histories of the readings of the take-off indicator, engine-speed indicator, and airspeed indicator. Airspeed below 50 knots was not plotted because the airspeed indicator was not designed to be read below this speed.

The first test was a normal take-off in which about 99 percent normal engine speed was maintained up to an airspeed of 77 knots. The take-off-indicator reading remained at about 380° which from the calibration of the instrument represented an initial excess thrust of 3,935 pounds. An oscillation of as much as ±10° or about $\pm 2\frac{1}{2}$ percent of full-scale deflection was superimposed on the mean level of the reading. The frequency of the oscillation did not correspond to the natural frequency of the instrument. Above 77 knots the nose wheel was apparently beginning to rise; this rise gave a spurious indication of increasing acceleration or thrust as a result of the increasing attitude angle.

A partial power failure during take-off was simulated for the second test. Engine speed was kept at 99 percent as in the previous test up to an airspeed of 55 knots. The indicator reading was very nearly the same as before (within 5° on the average or about 1 percent of the previous indication) and thus indicates that the attitude angle of the airplane remained essentially the same for successive take-offs. When the engine speed was reduced abruptly from 99 to 90 percent of rated speed, the take-off indicator responded quickly; that is, it changed from a mean level reading of 375° to 292°. This change represents a reduction in initial excess thrust of 1,050 pounds. The change in static thrust for the indicated change in engine speed is shown by the engine manual to be 1,150 pounds. When the engine speed was restored to 99 percent at about 80 knots, the take-off indicator reading returned to its initial value. In this case, the nose-wheel lift-off with the associated false indication of increased thrust apparently started at about 85 to 90 knots.

A partial power loss throughout the take-off was simulated in the third test. Engine speed of approximately 94 percent normal was maintained. This time the camera was turned on in time to record the windup of the take-off indicator needle. After release of the brakes, the needle quickly rotated to and remained at around 330° up to a velocity of about 60 knots. Then, apparently as a result of a slight engine-speed increase, the needle moved to 335° and remained in this position until a velocity of 80 knots was reached. The nose began lifting at about 80 knots. The reading of 330° on the take-off indicator represents an initial excess thrust of 3,315 pounds or a reduction of 575 pounds from the 99-percent engine-speed condition. For comparison, the reduction in static thrust as estimated from the engine manual was 700 pounds.

The 1-cycle-per-second fluctuation in the instrument reading which occurred in all tests is undesirable but tolerable. The false indication presented by the instrument after nose-wheel lift-off is started is not believed to be a serious fault, particularly if nose-wheel lift-off is delayed until after reaching the critical speed.

CONCLUDING REMARKS

An instrument is proposed which is designed to present to the pilot a constant predictable indication during take-off as long as the airplane is functioning normally as well as to show a rapid proportionate change in indication if a malfunction of the airplane causes a reduction in net accelerating force below normal.

Proper functioning of the instrument, which incorporates an accelerometer unit as a basic element, requires that the attitude angle of the airplane should not vary substantially during the part of the take-off of interest, that is, up to critical speed. Take-off measurements with three tricycle-geared airplanes including a large bomber, a jet fighter, and a jet trainer indicated that, for these cases, at least, this requirement was satisfied up to nose-wheel lift-off speed.

A preliminary test instrument, lacking the external adjustment and presetting provisions required for an operational version of the device, was tested in a jet trainer and its performance appeared to be satisfactory. The indicator responded quickly to changes in thrust simulating partial power failure. The reading was essentially constant for a given power setting up to the start of nose-wheel lift-off and was consistent for successive take-offs. A fluctuation of the indication of the instrument (1 cycle per second) of as much as 3 percent of the mean reading occurred in all tests; although this variation is undesirable, it was not considered a serious defect.

In view of the simplicity of this instrument, it should be reliable and free of service maintenance problems. It is felt that a take-off indicator of the proposed type merits consideration for improving safety in the take-off, particularly in cases where the take-off performance may be marginal.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., July 22, 1954.

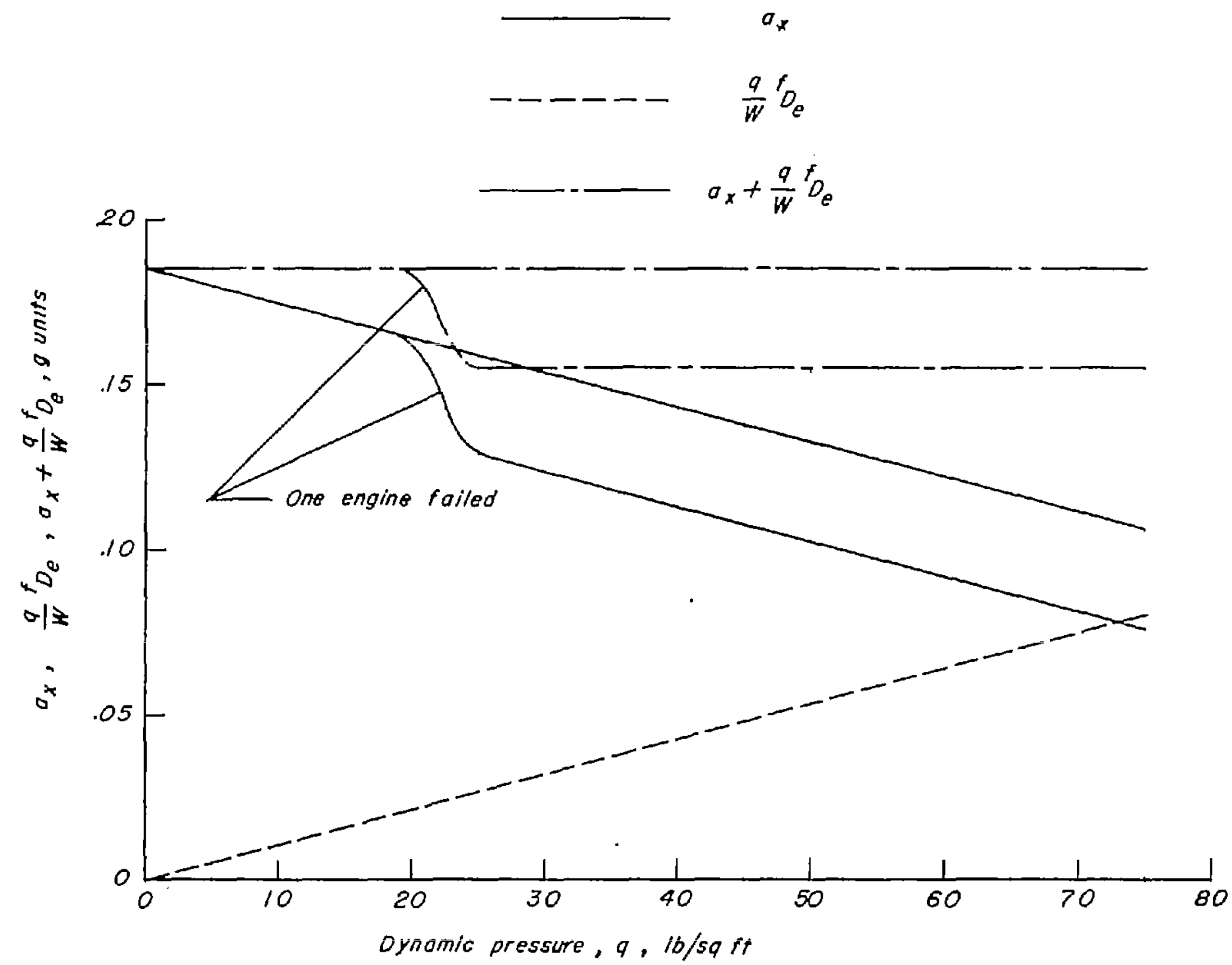


Figure 1.- Calculated variations with dynamic pressure of the acceleration and the term $\frac{q}{W} f_{D_e}$ for the take-off of a multiengine jet bomber.

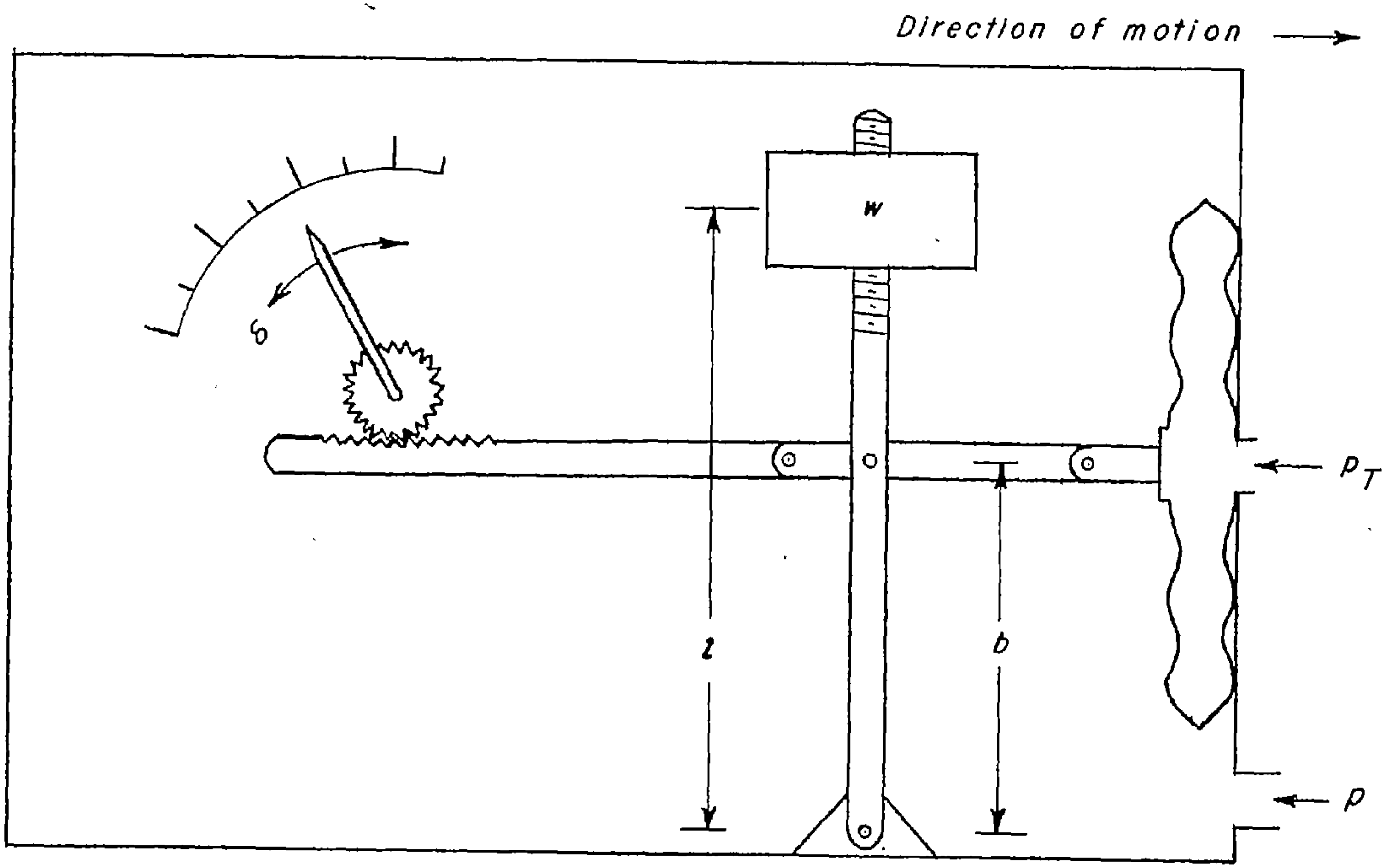
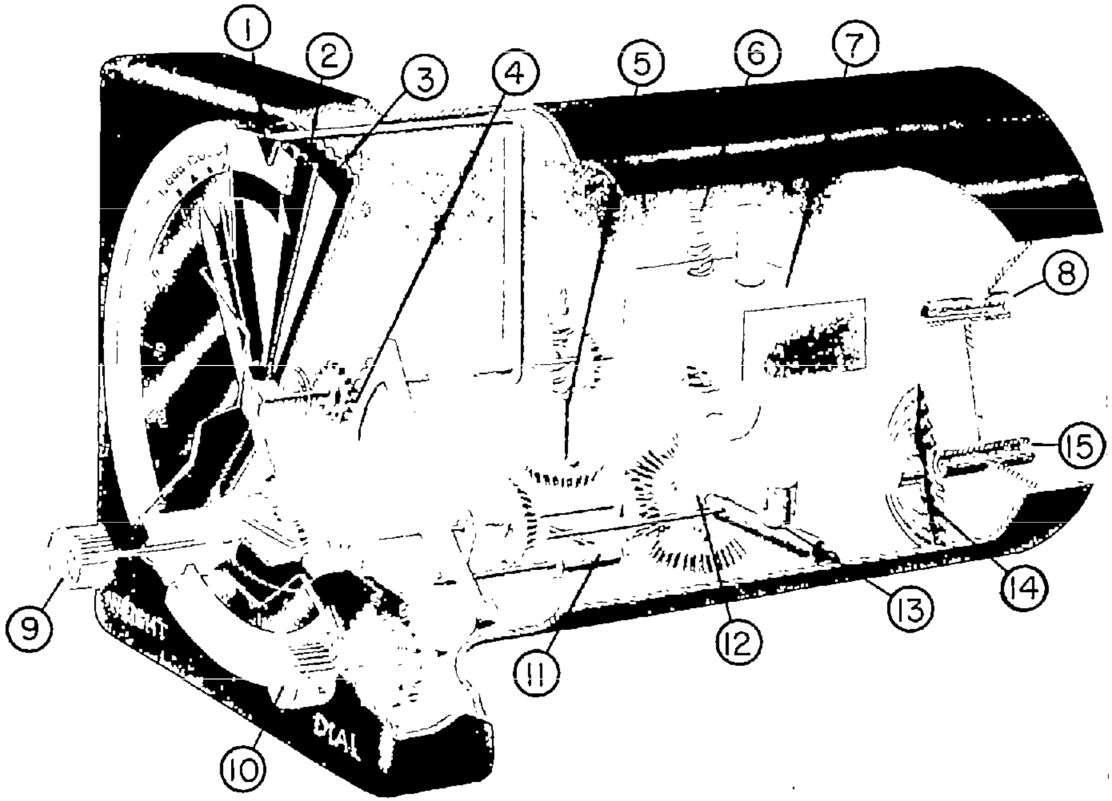


Figure 2.- Schematic sketch of the basic design of take-off instrument.



(1) Weight-adjustment indicator
(2) Dial
(3) Subdial
(4) Sector and pinion drive for indicator hand
(5) Gear assembly for driving airplane-weight-setting indicator
(6) Accelerometer-sensitivity adjusting screw
(7) Accelerometer mass
(8) Static-pressure inlet
(9) Knob for setting in airplane weight
(10) Knob for setting dial according to chart
(11) Rocking shaft
(12) Gear assembly for driving accelerometer adjusting screw
(13) Rocking shaft and linkage between diaphragm and accelerometer
(14) Airspeed diaphragm
(15) Total-pressure inlet

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Figure 3.- Illustrative arrangement of take-off indicator.

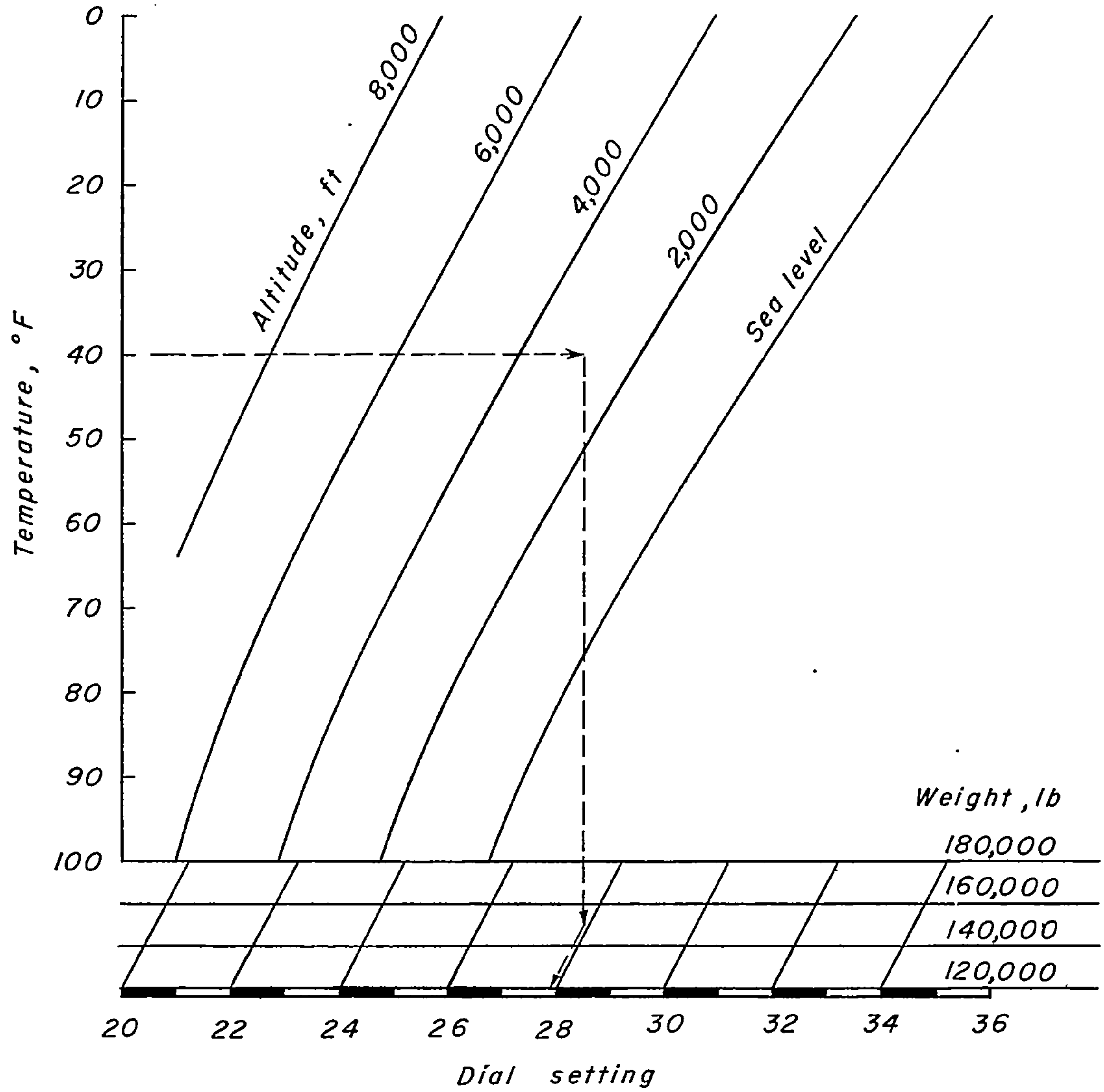

Figure 4.- Take-off chart for positioning dial setting of proposed instrument.

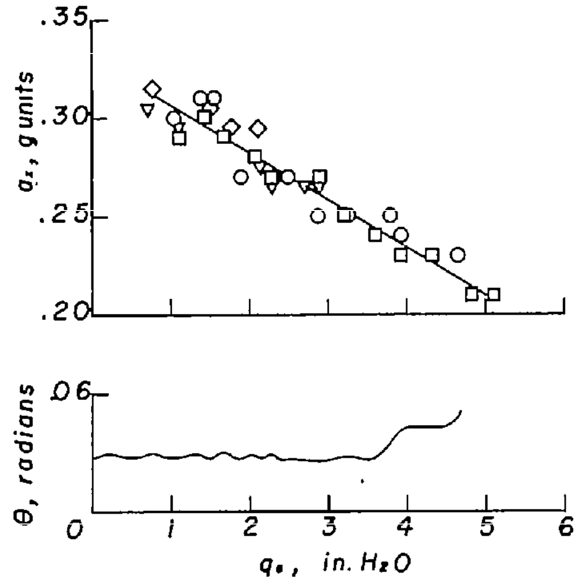

Figure 5.- Variation of longitudinal acceleration with impact pressure for several take-offs, and variation of attitude angle with impact pressure during one take-off of a multiengine propeller-driven bomber.

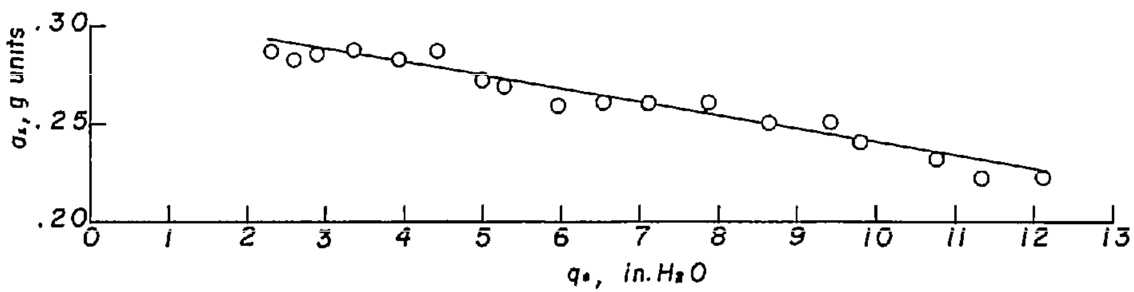

Figure 6.- Variation of longitudinal acceleration with impact pressure during the take-off of a jet fighter.

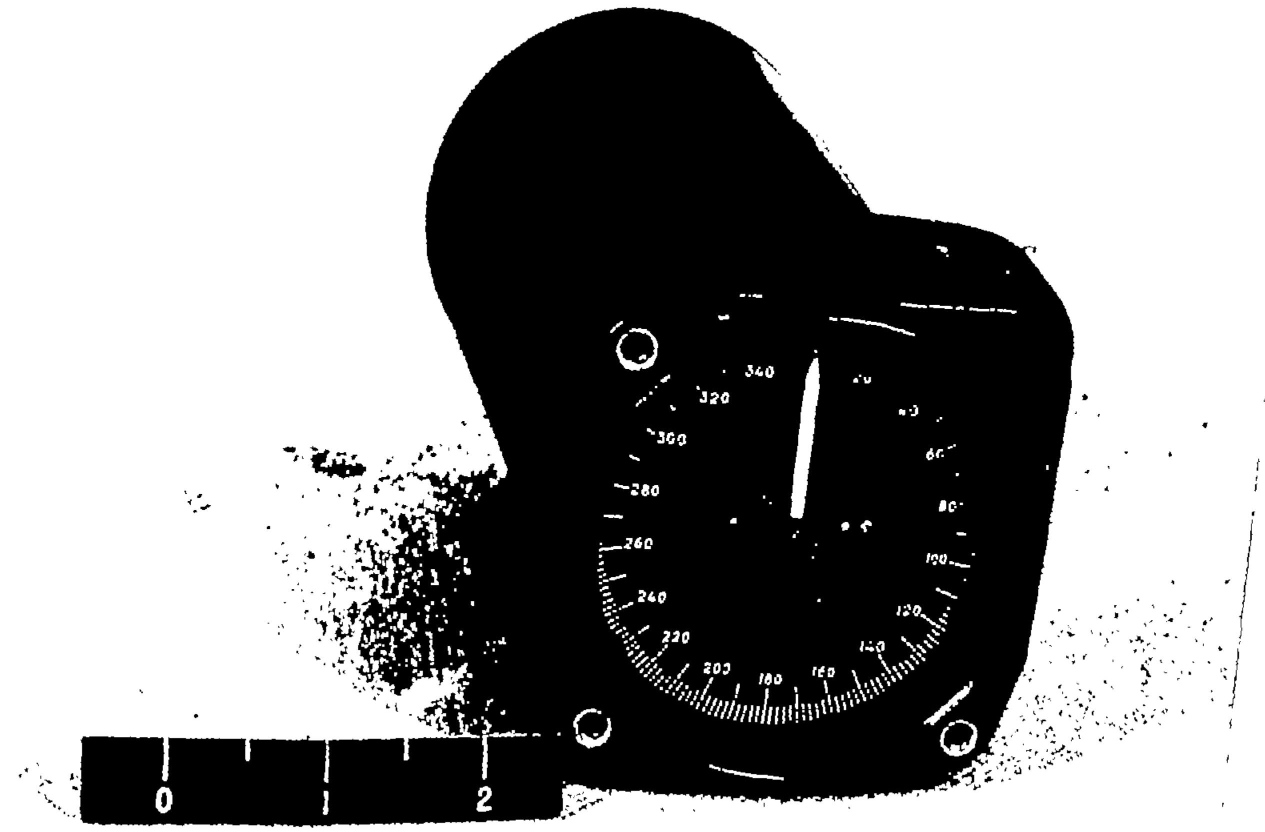

Figure 7.- Photograph of simplified prototype take-off indicator.

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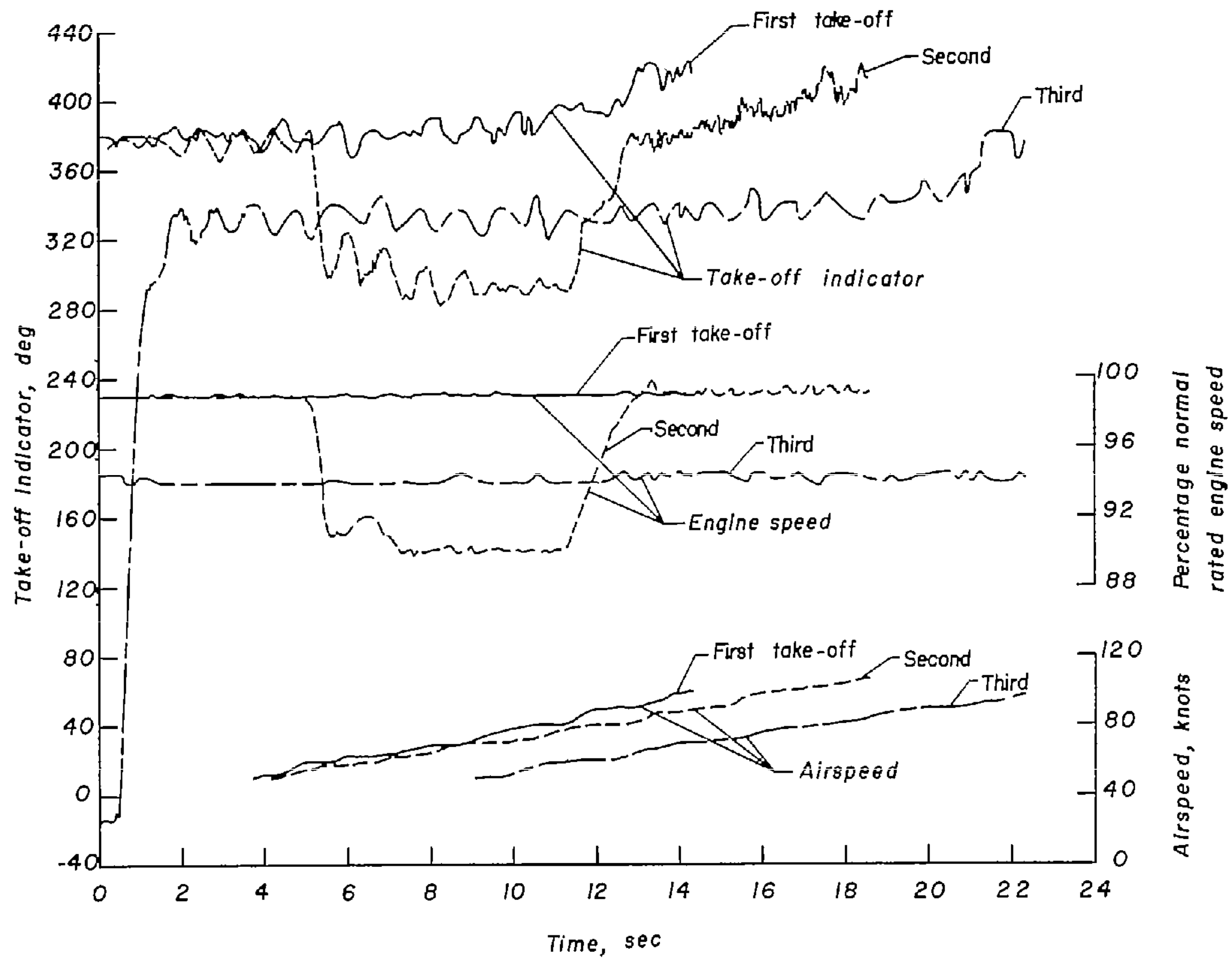

Figure 8.- Time history of readings of the take-off indicator, engine-speed indicator, and airspeed indicator of three take-offs of a jet trainer.

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